Google:[Leonid Zakharov] $\longrightarrow$ http://w3.pppl.gov/~zakharov

The kink mode during the disruptions in tokamaks[1]

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[1] This work is supported by US DoE contract No. DE–AC020–76–CHO–3073.

Contents

Abstract

The talk explains the locked $m/n = 1/1$ kink mode during the vertical disruption event when the plasma has an electrical contact with the plasma facing conducting surfaces. It is shown that the kink perturbation can be in equilibrium state even with a stable safety factor $q > 1$, if the halo currents, excited by the kink mode, can flow through the conducting structure. This suggests a new explanation of the toroidal asymmetry in magnetic measurements and so-called sideway forces on the in-vessel components during the disruption event.

In addition, the talk confirms the fundamental role of the halo currents (named here as "Hiro" currents), which interaction with the free boundary kink modes was in many occasions emphasized earlier by Hiro Takahashi and Eric Fredrickson. In fact, the physics of Hiro currents can explain four edge plasma stability regimes in tokamaks in a way consistent with DIII-D experiments.

EFDA JET

Disruption Forces and Halo Currents in JET

December 2007

Peter de Vries, Mike Johnson, Fabien Lanoy, Valeria Riccardo

1 Disruption Forces and Halo Currents in JET – December 2007 - by Peter de Vries

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1 Several slides from JET (cont.)

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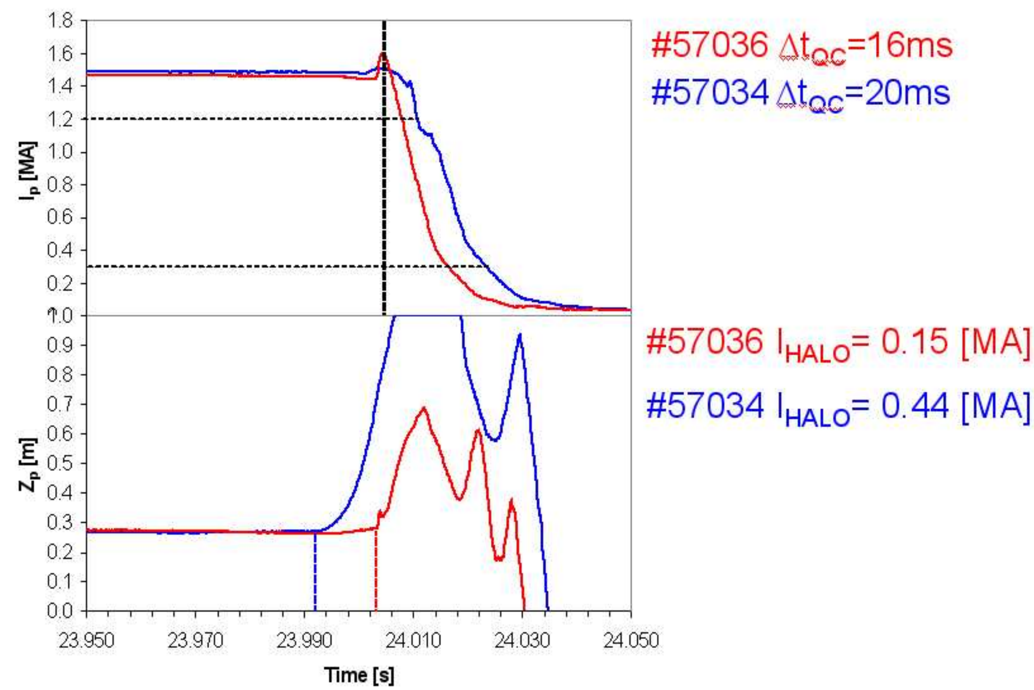
Two extreme cases

- For ITER-like configuration and plasma current (I_p=1.5MA)
  - Same Δt_{QC} but large halo currents and large disruption force
  - Same Δt_{QC} but small halo currents and small disruption force



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1 Several slides from JET (cont.)

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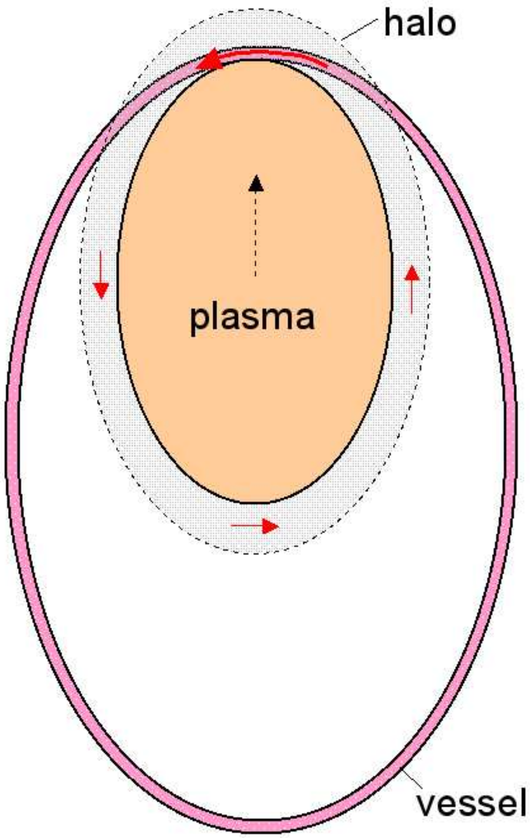
Halo Currents



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Introduction

- A disruption is a sudden (~20ms) loss of control and/or confinement of a tokamak plasmas.
  - Loss of vertical stability $\rightarrow$ Vertical Displacement Event (VDE)
  - Loss of confinement: energy quench $\rightarrow$ current quench (QC)
- The causes of disruptions are plentiful, often related to MHD stability or vertical stability.
- Disruptions could cause considerable damage to the structure of the tokamak device
  - Energy quench $\rightarrow$ large heat loads on in-vessel components
    - In JET up to $2MJ/m^2$.
  - QC and VDE $\rightarrow$ Large electromagnetic forces on the surrounding structures.
    - In JET forces on the vacuum vessel up to 750Tonnes (7.5MN).

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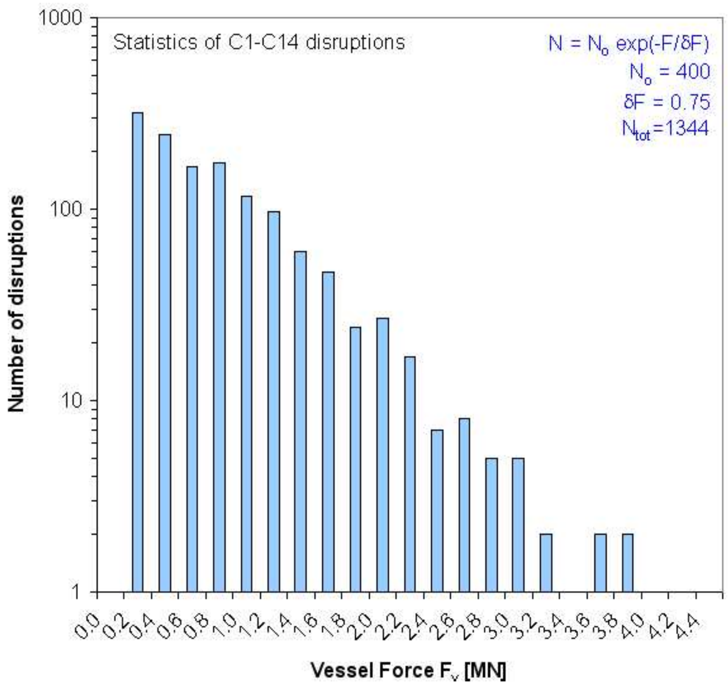
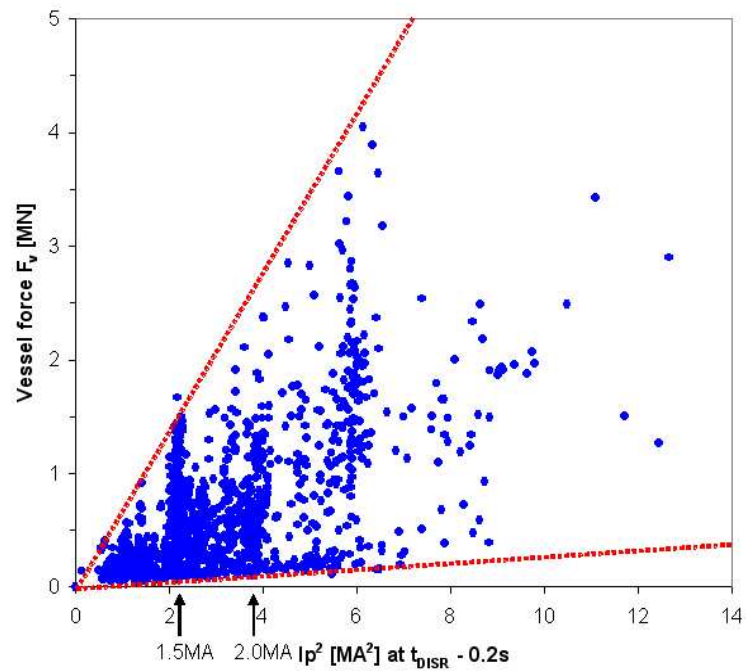
Disruption forces on JET

- There is a large spread in measured disruption forces on JET
  - Even if normalised to I_p^2.





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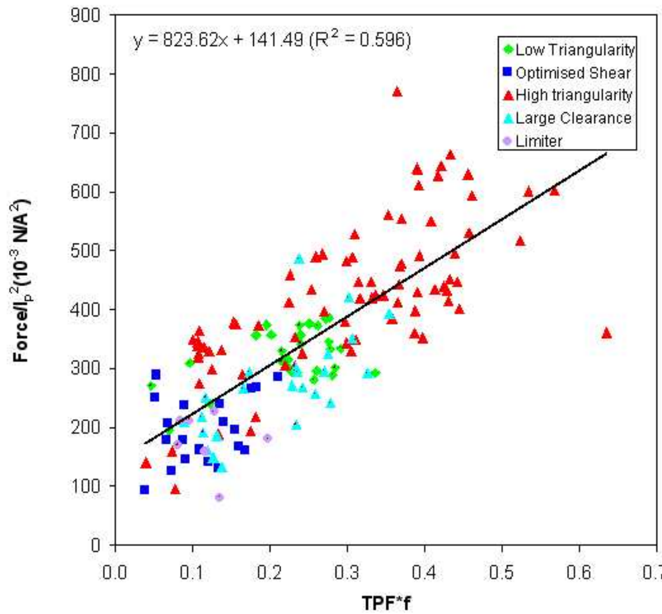
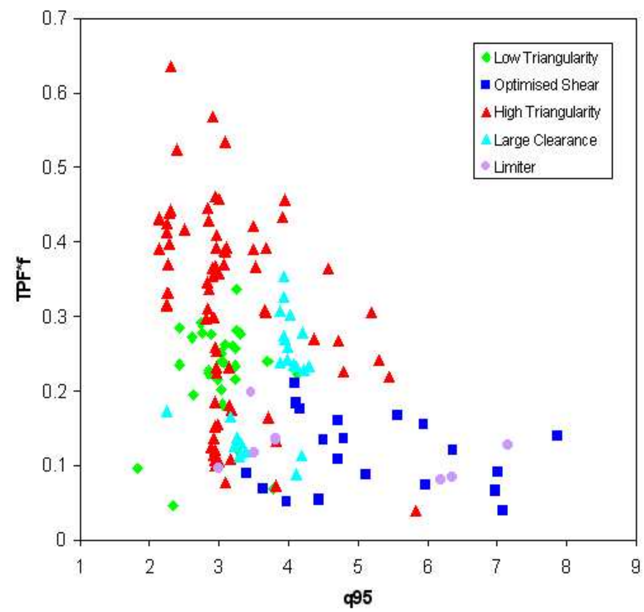
Halo currents and Forces

- Forces scale with the Halo currents on JET
  - Dominant source for the disruption forces on JET is due to halo currents
  - Although a distinct off-set is found (Coil forces? Eddy's?)
  - Halo currents (TPF x f) are smaller for higher q_{95}.[1]





[1] V. Riccardo, et al., PPCF **46** (2004) p925

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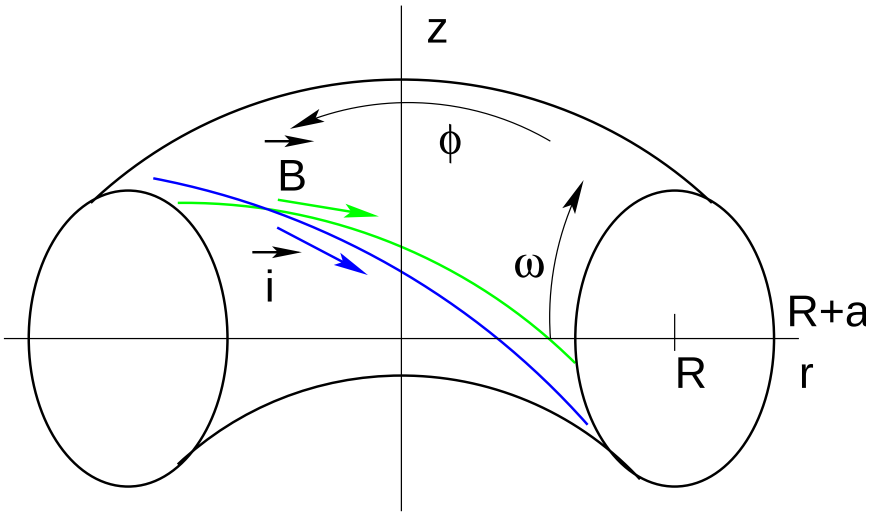
2 The basics of the kink mode in the presence of the halo currents

Deformation of the free plasma surface generates the surface current



$$\begin{aligned} r &= R - \rho\cos\omega, \\ z &= \rho\sin\omega, \\ \rho &= a + \xi(\omega,\varphi), \\ q &= \frac{aB_\varphi}{RB_\omega}, \end{aligned} \qquad (2.1)$$

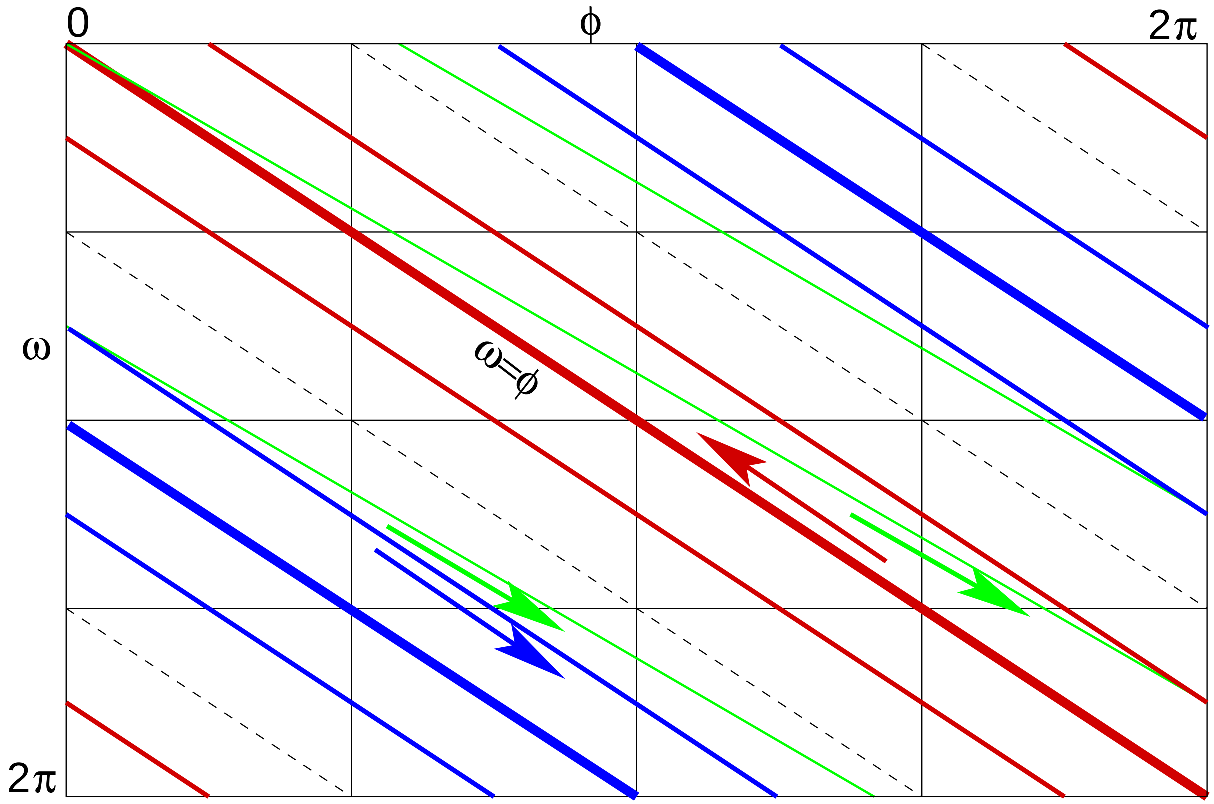
Its value is determined by the condition

$$\vec{\mathrm{B}} \cdot \nabla\rho = 0. \qquad (2.2)$$

If the plasma core is deformed in accordance with equilibrium conditions the only force acting on the plasma is the electromagnetic pressure

$$p_{j\times B}\nabla\rho = \vec{\mathrm{i}} \times \vec{\mathrm{B}}. \qquad (2.3)$$

For stable plasma the pressure suppresses the perturbation



Green is for $\overrightarrow{\mathrm{B}}$-lines.

Direction of the surface current:

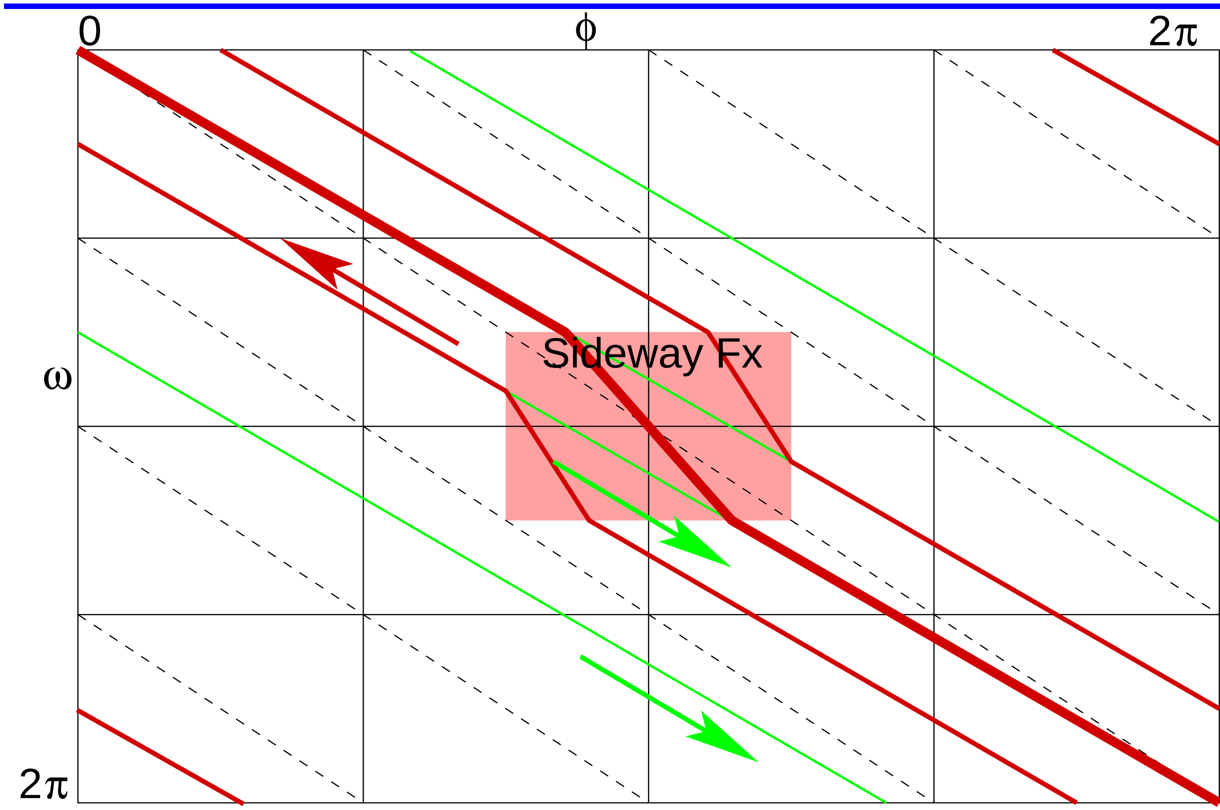
Blue lines are for current along B_φ

Red is for currents opposite to B_φ

Surface currents will be related to experimental measurements of $I_{pl}(\varphi)$ and the toroidal peaking factor (TPF)

$$\mu_0 \overrightarrow{\mathrm{i}} = -\xi_{11}\frac{2B_\varphi}{R}\cos(\omega-\varphi)\mathrm{e}_\varphi - \frac{1}{R}\xi_{11}\frac{2aB_\varphi}{R^2}\sin(\omega-\varphi)\mathrm{e}_\omega. \quad (2.4)$$

If $q > 1$ the kink mode 1/1 is stable (Shafranov, 1952)



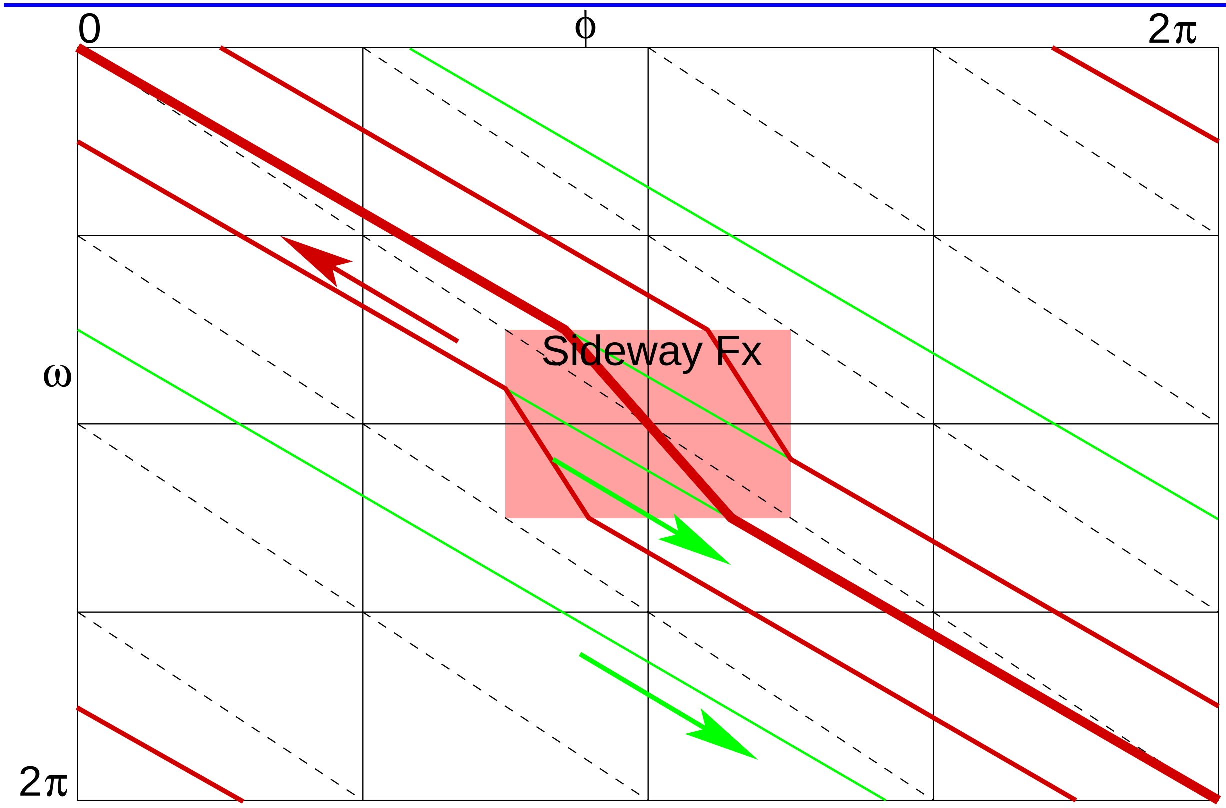
The presence of the wet-zone makes the stable plasma unstable.

Electromagnetic pressure is applied to the in-vessel conductors

$$\vec{\mathrm{i}}(\omega,\varphi) = -\frac{1}{a} I'_\omega \vec{\mathrm{e}}_\varphi + \frac{1}{R} I'_\varphi \vec{\mathrm{e}}_\omega, \qquad (2.5)$$

$$F_x = \pi I_{pl} B_\varphi (1-q)\xi_{11},$$

Depending on the position of the wet-spot a troublesome sideway force can be generated



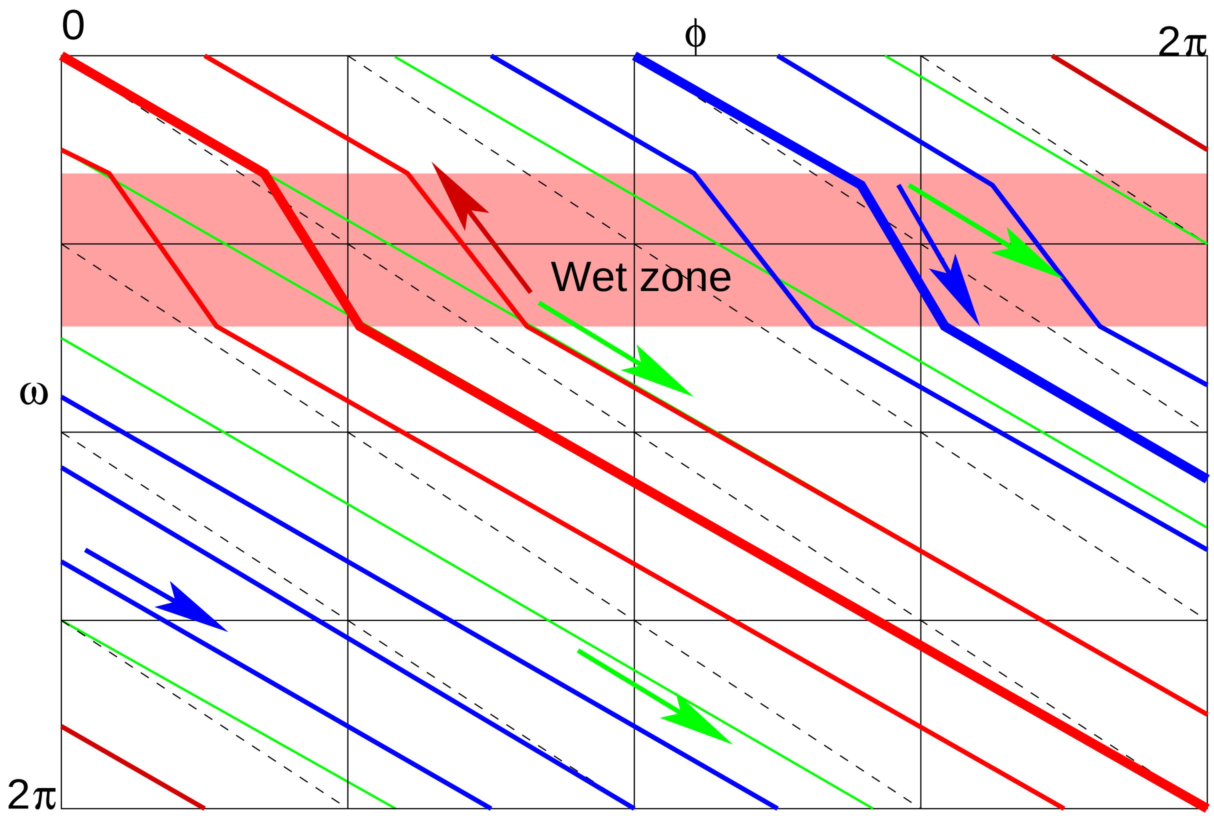
There is a finite size

$$\frac{\Delta\omega}{2\pi} = \frac{q-1}{q} \quad (2.6)$$

of the wet-zone for excitation of the kink mode.

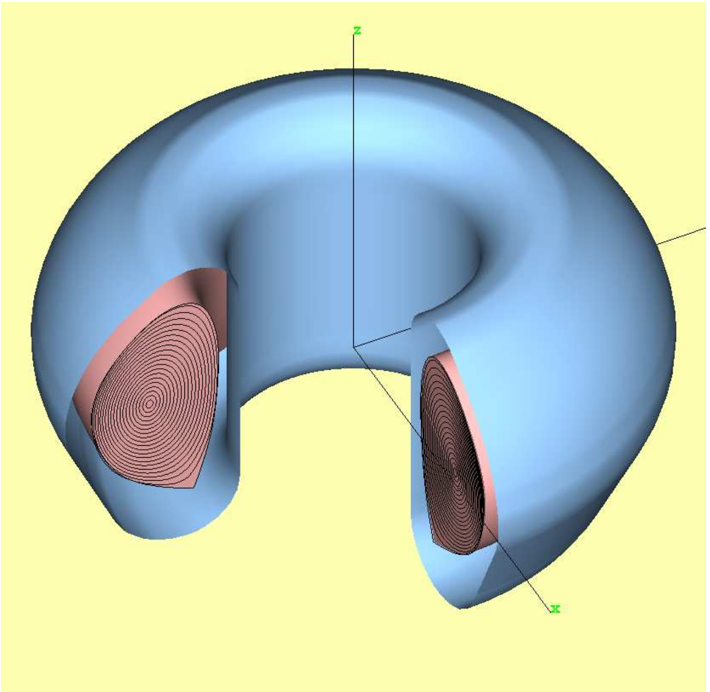
If the wet-zone is self-generated, then there is a threshold for instability

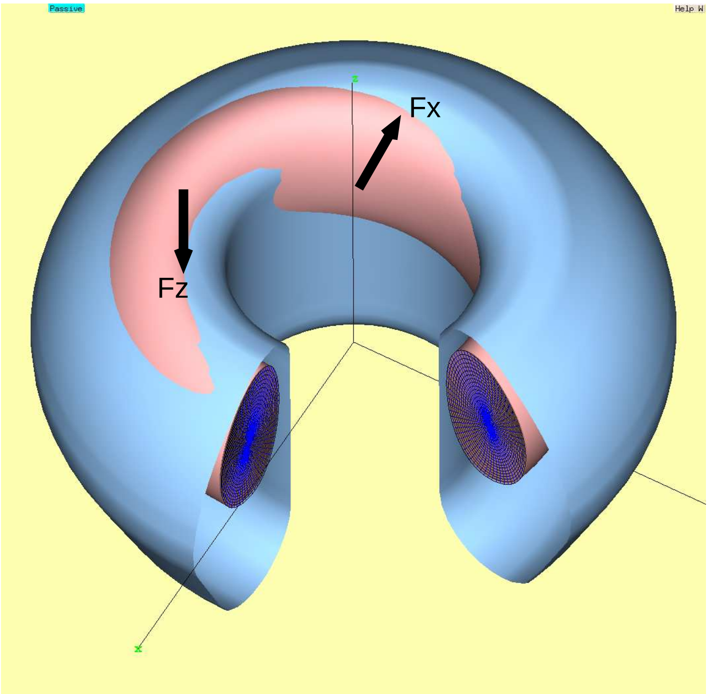
Kink-mode is linearly unstable in the case of axisymmetric wet-zone, e.g. at the vertical disruption events (VDE)



At the nonlinear stage the mode leads to a disbalance in plasma current measurements at different azimuths φ (TPF)

The force is applied to the wet-spot and is directed toward the plasma





Both thermal and current quench make the vertical equilibrium field

$$B_{z,ext} = -\frac{0.1 I_{pl}}{R}\left(\ln\frac{8R}{a} + \beta_j + \frac{l_i}{2} - \frac{3}{2}\right), \quad \beta_j \rightarrow 0 \qquad (2.7)$$

becomes excesive and pushes plasma inward, leading to the sideway force.

The trajectory of the plasma during VDEs depends on equilibrium

3 The theory of the Tokamak Kink Mode (TKM)

All the theory is reduced to relationship between ξ and i

For arbitrary m, n and pereturbation of the form

$$\rho = a + \Re\left(\sum_{m,n} \xi_{mn} e^{im\omega - in\varphi}\right), \qquad (3.1)$$

the surface currents are determined by the perturbed equilibrium theory (Zakharov, Sov.J. Plasma Physics,(1981), Reviews of Plasma Phys. v.11*)*

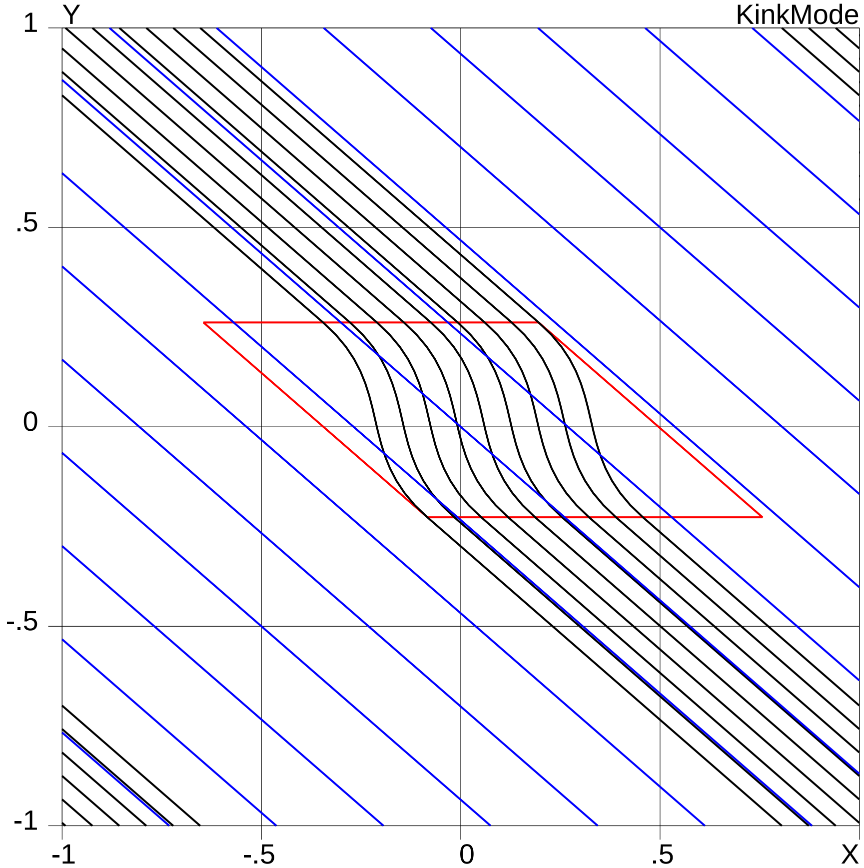
$$\begin{aligned} \overrightarrow{\mathrm{i}} &= \nabla I(\omega,\varphi) \times \overrightarrow{\mathrm{e}}_n = -\frac{1}{a} I'_\omega \overrightarrow{\mathrm{e}}_\varphi + \frac{1}{R} I'_\varphi \overrightarrow{\mathrm{e}}_\omega, \\ i_(\omega,\varphi) &\equiv \Re\left(\sum_{m,n} i_{nm,\varphi} e^{im\omega - in\varphi}\right), \qquad (3.2) \\ \mu_0 i_{mn,\varphi} &= \xi_{nm}\left[(m-1)j - \frac{2nB_\varphi}{R}\right] e^{im\omega - in\varphi} \end{aligned}$$

The electromagnetic pressure is given (for a uniform current density) by

$$p = 2I_{pl}B_\omega \Re\left(\sum_{nm} \xi_{nm} \frac{nq - m + 1}{m} (m - nq)\, e^{im\omega - in\varphi}\right), \qquad (3.3)$$

Together with electro-dynamics of the vacuum vessel they are sufficent for simulation of disruptions

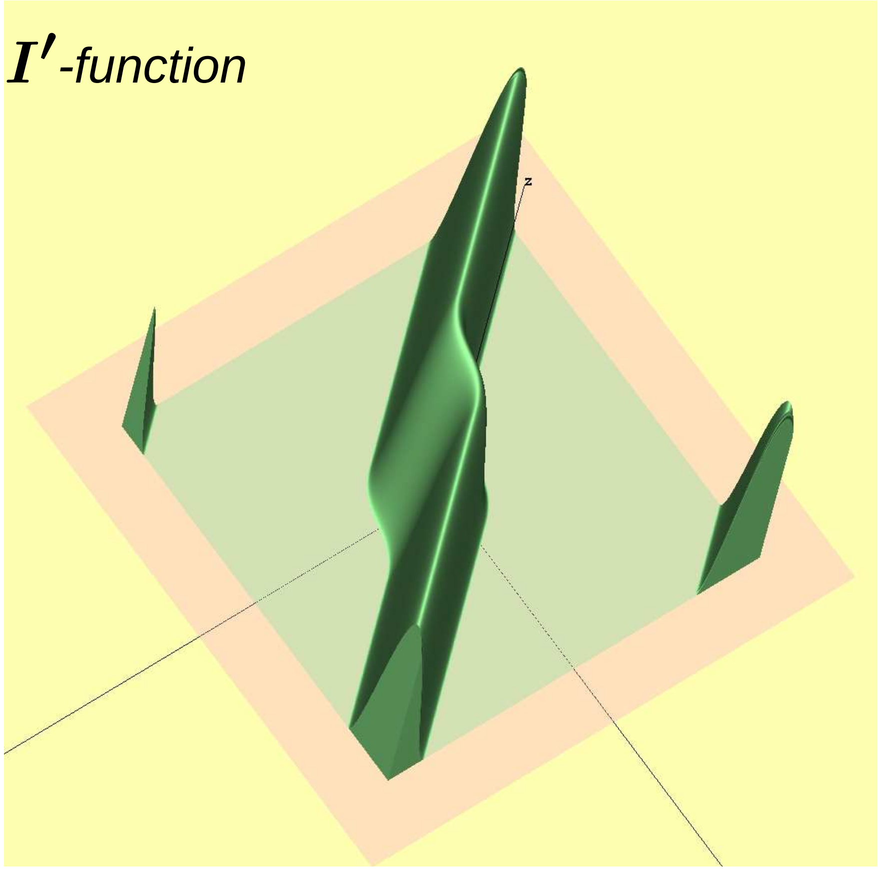
Eq.(3.3) converts surface current into plasma displacement

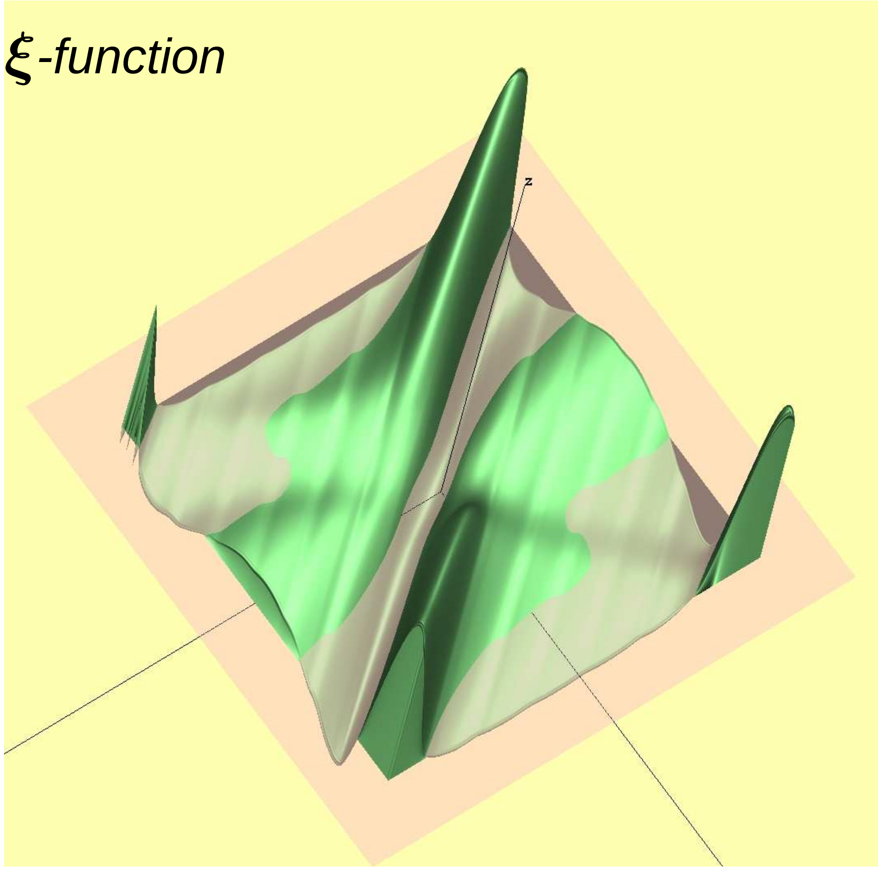


$$\begin{aligned}
\vec{\mathrm{i}} &= \nabla I(\omega,\varphi) \times \vec{\mathrm{e}}_n,\\
I(\omega,\varphi) &= I(x),\\
x &= x(\omega,\varphi),\\
\vec{\mathrm{i}} &= -\frac{I'}{a} x'_\omega \vec{\mathrm{e}}_\varphi + \frac{I'}{R} x'_\varphi \vec{\mathrm{e}}_\omega
\end{aligned} \tag{3.4}$$

The figure shows the current flow lines $x = const$ *of the halo currents*

Eq.(3.3) converts surface current into plasma displacement



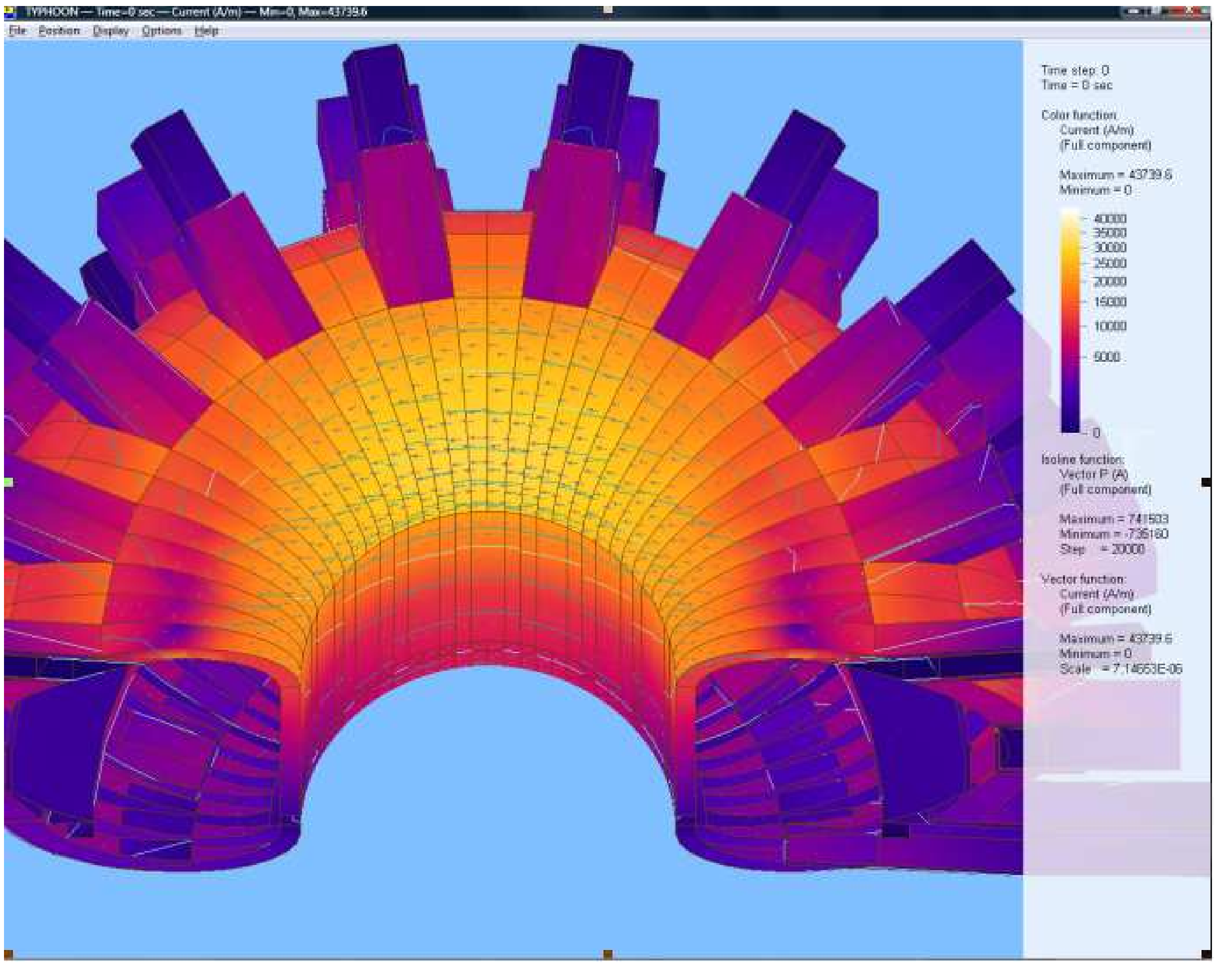


Even this hand-prescribed current profile reveals that

The shape of the surface displacement is consistent with the halo current supply in the wet-zone

3 Theory of the Tokamak Kink Mode (TKM) (cont.)

Theory of TKM should be linked with the electro-magnetic modeling



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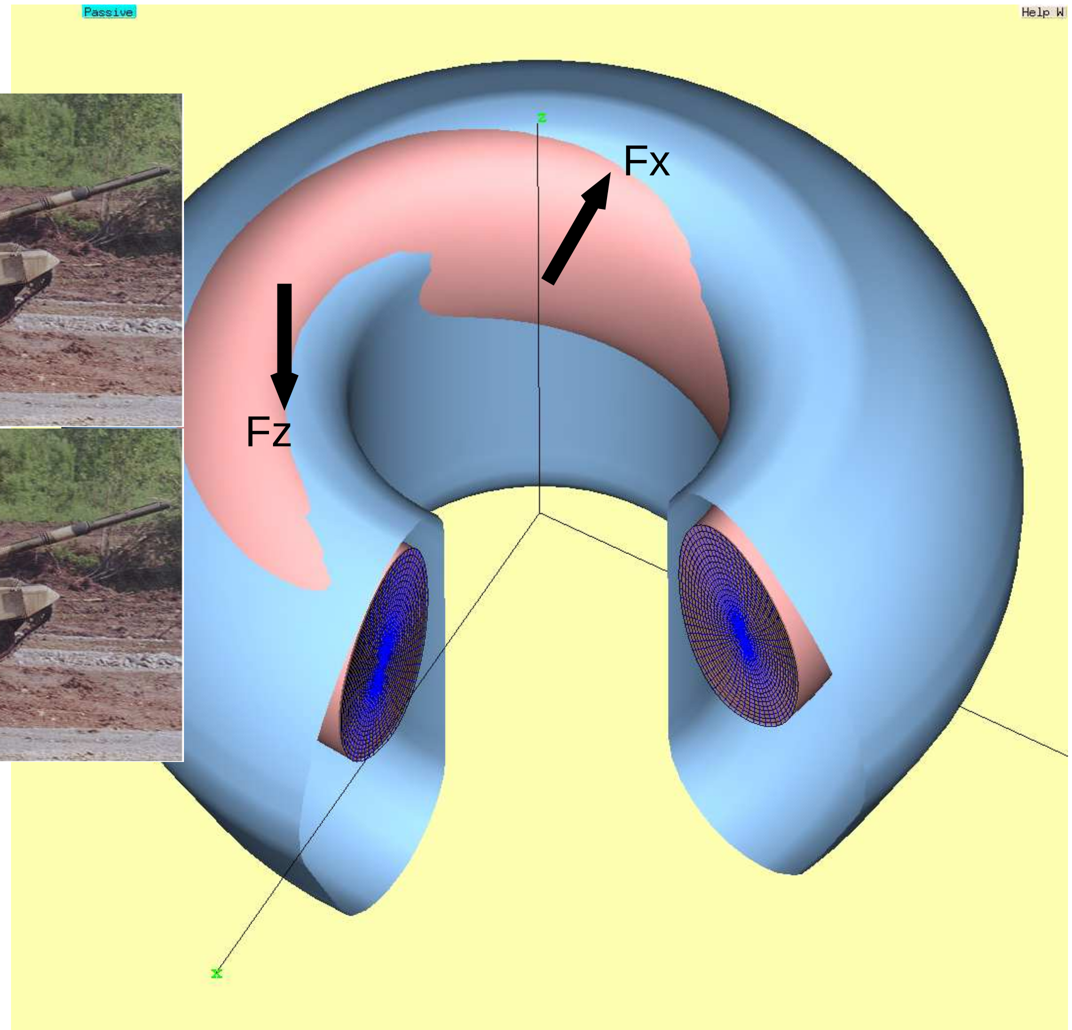
3 The theory of the Tokamak Kink Mode (TKM) (cont.)

The momentum $\simeq 2MN \cdot sec$ of the sideway force in ITER is equivalent to the hit of its VV by two 50 T T-90S tanks at the speed of 70 km/hour.



When applied to the quasi-stable plasmas, TKM stands for “Takahashi Kink Mode”

Hiro Takahashi and Eric Fredrickson revealed the apparent role of helical halo currents (“Hiro’s currents”) associated with the free boundary instabilities in DIII-D

Unlike in disruptions, in quasi-stationary plasmas the halo currents are limited by the ion-saturation current I_{ion}

The ion-saturation current is determined by the plasma particle flux to the wall

$$I_{ion,A} = 1.6 \cdot 10^{-19} \left.\frac{dN}{dt}\right|^{edge-wall},$$

$$\left.\frac{dN}{dt}\right|^{edge-wall} = \frac{1}{1-R_{rec}} \cdot \left.\frac{dN}{dt}\right|^{core-edge} \simeq \frac{1}{1-R_{rec}} \cdot \frac{N}{\tau_p}, \qquad (4.1)$$

$$\frac{N}{\tau_p} \simeq 10^{22} \frac{1}{sec}$$

The Hiro currents I_H are limited by

$$I_H < I_{ion} \frac{\Delta_H}{\Delta_{SoL}}. \qquad (4.2)$$

The Hiro currents introduce into stability theory two factors related to the plasma density

In collisionless SOL the Δ_H is related to the ion collisonless skin depth d_i

In collisionless SOL (with no emission from the plates) the ion inertia determines the Hiro current

$$\begin{aligned}&\overrightarrow{\widetilde{\mathrm{B}}} \equiv \nabla\psi \times \vec{e}_s, \quad \frac{e}{c}\cdot\frac{\partial\psi}{\partial t} = m_i\frac{dV_i}{dt},\\ &enV_i = \frac{1}{2}j_H = -\frac{1}{2}\cdot\frac{c}{4\pi}\Delta\psi,\\ &\frac{\partial}{\partial t}\left(\psi + d_i^{*2}\Delta\psi\right) = 0_{resistive}, \quad d_i^* \equiv \frac{d_i}{\sqrt{2}} = \frac{c}{\sqrt{2}\omega_{pi}}\end{aligned} \qquad (4.3)$$

The $d^*_{i,cm}$ parameter determines the value of I_H and the plasma edge stability regime

The Hiro currents depth Δ_H *is limited by*

$$\Delta_H \simeq \min\{d_i, \Delta_{SOL}\} \qquad (4.4)$$

Four plasma edge stability regimes can be specified

1. The LiWF regime, $d_i^* \gg \Delta_{SoL}$. *Negligible Hiro currents.*

$$d_{i,cm}^* \simeq \frac{2.3}{\sqrt{n_{20}^{edge}}} \gg \Delta_{SoL} \qquad (4.5)$$

Low recycling, low plasma density, no ELMs, no blobs, perfectly stable plasma egde. Exactly like in DIII-D experiments

2. The ELMy H-mode, $d_i^* \simeq \Delta_{SoL}$. *Limited Hiro currents, reduced recycling. Resistive effects leads to relaxations.*

3. L-mode, $d_i^* < \Delta_{SoL}$. *Unlimited Hiro currents, total mess with blobs.*

$$\pi i_H = \frac{I_{pl}}{a^2} \xi_{nm} \left(nq_{left} - nq \right) \qquad (4.6)$$

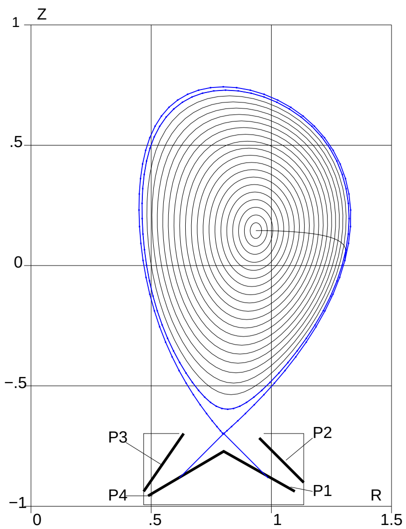
4. High density disruptions, $d_i^* < \Delta_{SoL}$. *Feed back between plasma core and the Hiro currents.*

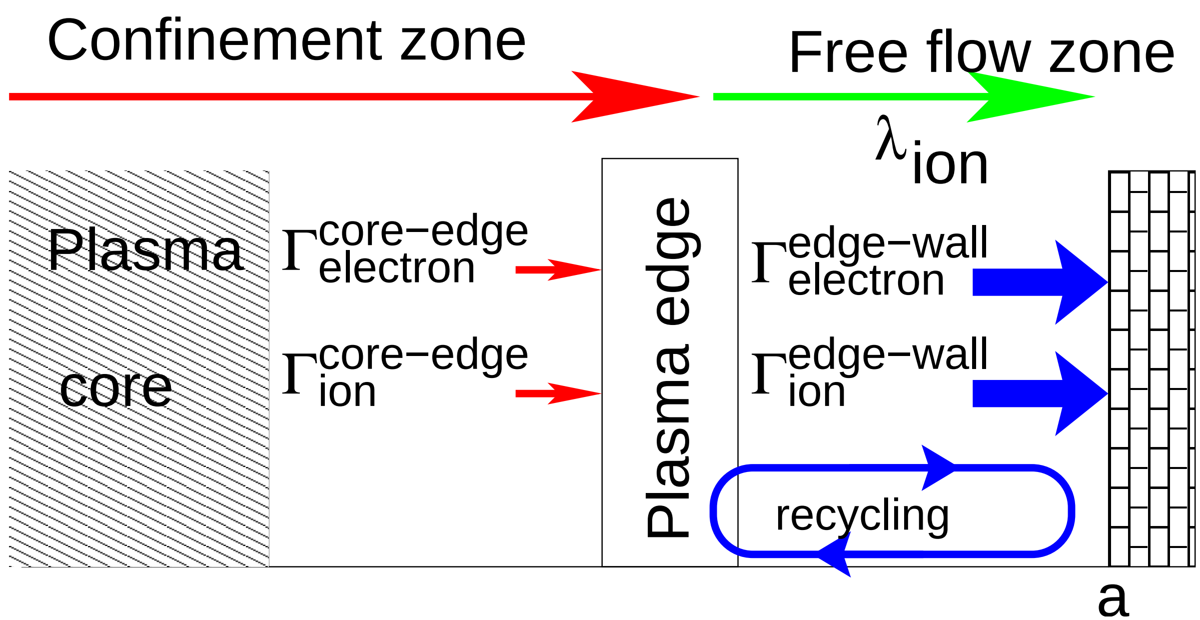
$$\begin{aligned} i_H &\simeq \frac{I_{ion}}{2a} \simeq \frac{en^{edge}4\pi^2 Ra}{2a}\gamma\xi, \\ 2\pi^3 Ra\gamma e \cdot n^{edge} &< \frac{I_{pl}}{a}\left(nq_{left} - nq\right) \end{aligned} \tag{4.7}$$

The plasma edge density explicitly enters into tokamak MHD stability condition.

The mean free path, λ_D defines the position of the plasma edge

$$\lambda_{D,m} = 121\frac{T_{keV}^2}{n_{20}} \tag{4.8}$$

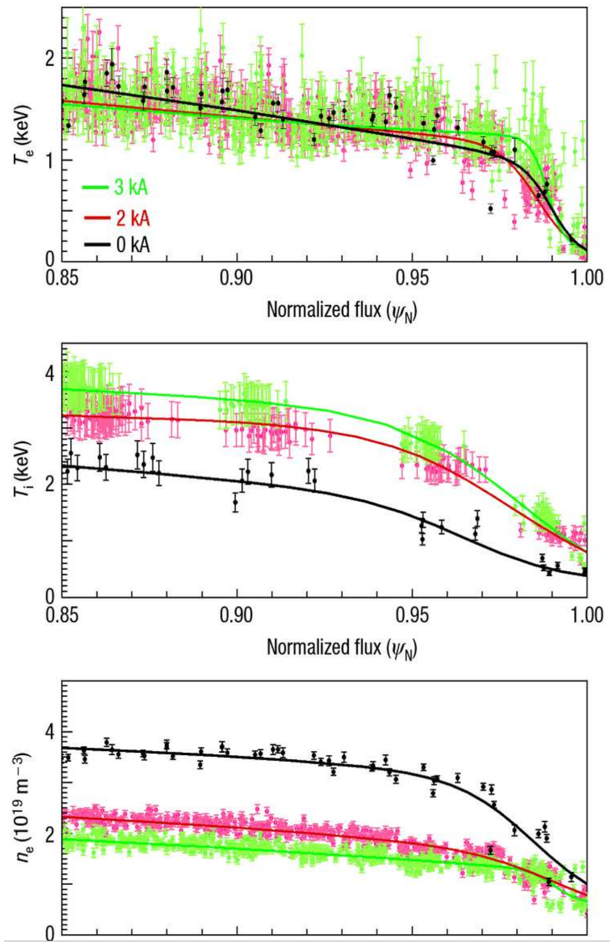


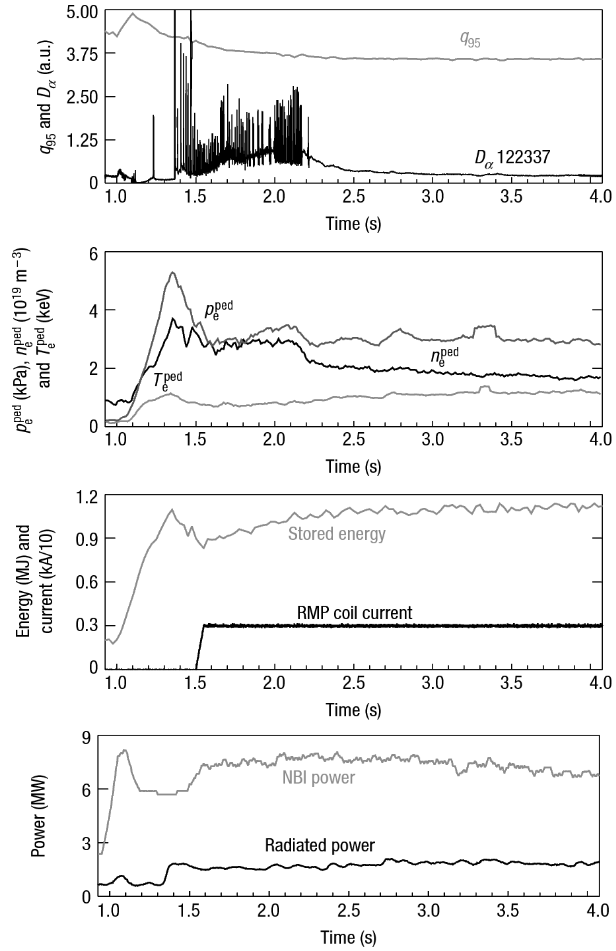


At the plasma edge the temperatures are determined by particle fluxes

$$\frac{5}{2}\Gamma^{edge-wall}_{i,e} T^{edge}_{i,e} = \int_V P_{i,e} dV \tag{4.9}$$

The plasma edge is at the temperature pedestal





0 kA, 2 kA, 3 kA $I_{RMP-coil}$ *T.Evans at al., Nature physics 2, p.419, (2006)*

There is no confinement behind the plasma edge

ELMs, blobs, beginning of high density disruptions seem to be just the different types of Takahashi Kink Modes

At the same time, the TKMs, which are always unstable, are the primary candidate for determining the width of the edge temperature pedestal, where the confinement is destroyed.

Suppresion of Hiro currents and TKM automatically leads to sharpening of the edge T-pedestal, in consistency with Todd's Evans observations in RPM experiments on DIII-D.

The long lasting misconception of ***"the edge transport barrier"****, based on naive static model of near-separatrix layer* ***has nothing in common with the reality****.*

In fact, the so-called "edge transport barrier" is the NO-confinement zone

1. The theory of the Tokamak Kink Mode explains the behavior of MHD instabilities in the REAL tokamak environment
2. Through the physics of Hiro currents, the edge plasma density was finally introduced into MHD theory as a decisive element of tokamak stability.

It is proved once again how consistent with the plasma physics and stability is the LiWF (delayed by 10 years in PPPL)

This regime can be described by the well-understood, ideal MHD model.

At the same time, the understanding of stability in the conventional fusion can be illustrated by

VOLUME 51, NUMBER 23 PHYSICAL REVIEW LETTERS 5 DECEMBER 1983

Stabilization of External Kink Modes by Means of a Limiter

J. P. Freidberg, J. P. Goedbloed,[a] and R. Rohatgi
Plasma Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 9 August 1983)

It is shown that poloidal ring limiters are very effective in stabilizing ideal external kink modes in a tokamak. With one poloidal limiter all external modes are stable for $q_a > 1$. However, toroidal limiters have negligible influence on stability. Reversed-field pinches require a finite number of poloidal limiters (typically six) to stabilize the strong external kink modes that would result if the conducting wall were removed.

PACS numbers: 52.35.Bj, 52.55.Gb

The absence of ideal external kinks in tokamak experiments has yet to be satisfactorily resolved. Theory indicates that without a conducting wall these modes would constrain tokamak operation to low-β, high-q regimes.[1] Invoking the relatively-low-conductivity vacuum chamber as an ideal wall is unsatisfactory, as it fails to explain the absence of "resistively slowed" unstable external kinks. Assuming the stabilization to be due to

in order to satisfy the constraint $\xi_r(a, \theta = 0, \varphi) = 0$. More complicated limiters (rails, "mushrooms," etc.) are also similar in that they constrain plasma motions and lead to stabilization, but have not been considered because of computational complexity.

The analysis is carried out with use of a "modified energy principle," $\mathfrak{L} = \delta W - \omega^2 K$, where $\delta W = \delta W_p + \delta W_s + \delta W_v$ are the usual plasma, surface,